Applications of Synthetic Aperture Radar to Meteorology and Oceanography Command Operations

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LONG-TERM GOALS

Our long-term goal is to employ near-surface wind speed derived from synthetic aperture radar (SAR) images of the sea surface as a marine meteorological research and forecasting tool. That is, we aim to use SAR-derived wind speed (SDWS) images to discover dynamical and morphological characteristics of microscale, mesoscale, and synoptic scale marine meteorological phenomena. We also aim to demonstrate how the fruits of our discovery can be used to aid marine meteorological analysts and forecasters.

OBJECTIVES

1. Develop software tools for portable, automated analysis of SDWS images with the objective of resolving intense mesoscale variability within those images.

2. Develop a SDWS-based system for automated verification of, and error-warning for, mesoscale near-surface wind field forecasts produced by numerical weather prediction (NWP) models. The emphasis is on verification and error detection in those regions most challenging to mesoscale NWP models—namely, the near-shore zones adjacent to complex topography.

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3. Empirically and theoretically investigate the SDWS-signature of convectively-driven squall / lull couplets. The analysis includes the forcing, structure, and predictability of these intense mesoscale variations in the near-surface wind speed field. The goal is to make incremental gains towards improved NWP model and statistical forecasts of this phenomenon.

In the context of these objectives, we have outlined five tasks:

Task 1. Develop a highly portable, efficient, and verifiable CMOD 4/5 hybrid software system for SDWS retrieval.

Task 2. Develop a fully automated system for mapping intense mesoscale variability in SDWS images.

Task 3. Determine the forcing, structure, and predictability of the convectively-driven open ocean squall / lull couplet features frequently seen within SDWS images.

Task 4. Develop a SDWS-based system for automated verification of, and error-warning for, mesoscale near-surface wind field forecasts produced by NWP models.

Task 5. Publish results in appropriate journals and present research at relevant conferences.

APPROACH

Our approach remains unchanged from that described in previous reports. The basis of this research is the approximately 35,000+ SDWS image frames from the Bering Sea, Gulf of Alaska, East Coast of the United States, and the North Atlantic Ocean (from 1998 to present) contained in an archive at The Johns Hopkins University Applied Physics Laboratory (JHUAPL). This data is provided at no cost by Dr. Winstead. The image archive has been used extensively by the PIs to study atmospheric phenomena in the Gulf of Alaska. In addition to the previous ONR-funded research of Drs. Sikora and Young (N00014-06-10046 [Sikora] and N00014-04-10539 [Young]), Drs. Winstead and Young participated in an NSF-sponsored study of barrier jets in the Gulf of Alaska using SDWS images. During the course of these research projects, a catalog of various imaged phenomena was generated by Drs. Sikora and Young (*Stepp et al.* 2007). This catalog documented a number of phenomena causing intense mesoscale variations in the near shore, near-surface wind speed field including: gap flow exit jets (Figure 1), topographic gravity waves (Figure 2), and island wakes (Figure 3). In the open ocean, the most intense near-surface wind speed variability was caused by quasi-circular squall / lull couplets (Figure 4) described in *Young et al.* [2007] and synoptic-scale atmospheric fronts (Figure 5) described in *Young et al.* [2005]. The approach described here is designed to automate the quantitative description of these intense mesoscale wind variations and form the basis for forecasting them via a combination of NWP and statistical post-processing methods.

The project is organized as a series of tasks in which each task builds on the preceding results. Task 1, the development of a highly portable, efficient, and verifiable CMOD 4/5 hybrid software system for SDWS retrieval, was completed two years ago and, thus, is not covered in this report. Similarly, Task 2, the development of a fully automated system for mapping intense mesoscale variability in SDWS images, was completed last year, with the results published [*Young et al.*, 2008]. Task 3, the determination of the forcing, structure, and predictability of the convectively-driven open ocean squall / lull couplet features frequently seen within SDWS images, was completed this year. Initial results

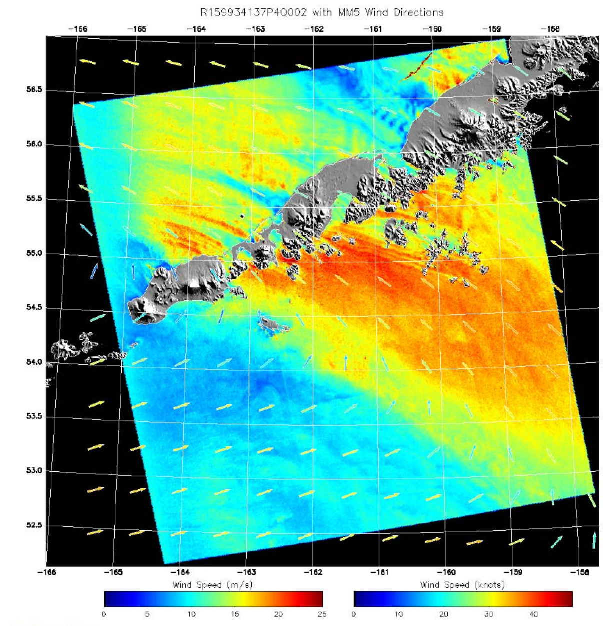

Figure 1. Radarsat-1 SDWS image depicting the signature of gap flow exit jets forced by stably-stratified flow through topography ahead of a front. Terrain-driven gravity waves and island wakes are also visible. The 600 m pixel image is 1200 pixels by 1200 pixels. The image was acquired over the Alaska Peninsula at 0426 UTC on 29 April 2007. The near-surface wind speed varies by 20 m/s across the front. Arrows indicate MM5 model winds. (Provided courtesy of JHUAPL)

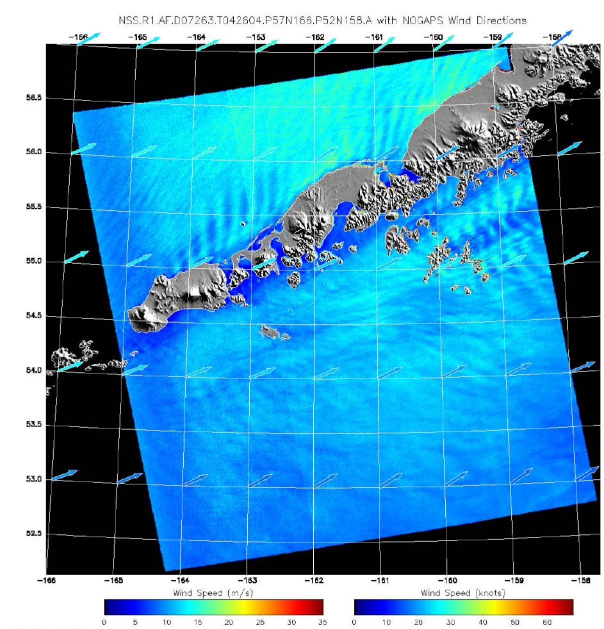

Figure 2. Radarsat-1 SDWS image depicting the signature of gravity waves forced by stably stratified flow over mountainous islands. The 600 m pixel image is 1200 pixels by 1200 pixels. The image was acquired off the Alaskan Peninsula at 0426 UTC on 20 September 2007. Arrows indicate NOGAPS model winds. (Provided courtesy of JHUAPL)

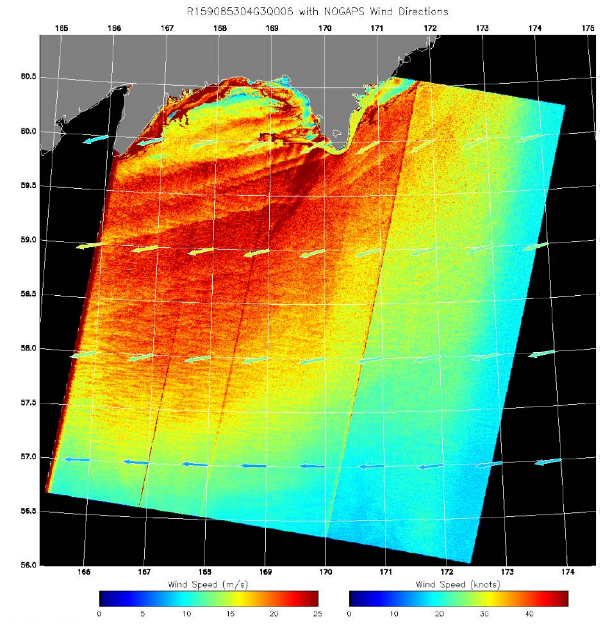

Figure 3. Radarsat-1 SDWS image depicting the signature of slow wakes forced by turbulent flow over a mountainous peninsula and the bow shocks caused by flow past the tip of the peninsula. The 600 m image is 1200 pixels by 1200 pixels. The image was acquired off the Siberian coast at 1833 UTC on 28 February 2008. The near-surface wind speed varies from strong breeze to storm in these terrain-driven mesoscale flows. Arrows indicate NOGAPS model winds. (Provided courtesy of JHUAPL)

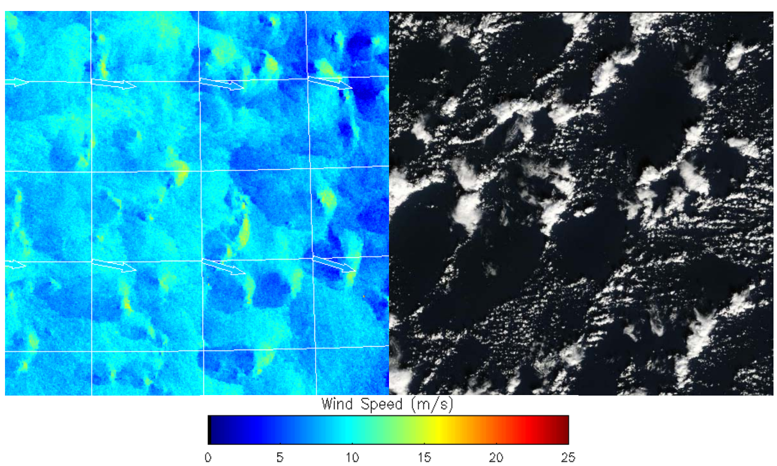

Figure 4. At left is a Radarsat-1 SDWS image depicting the quasi-circular signatures of convectively-driven open ocean squall / lull couplets. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired over the Gulf of Alaska at 0301 UTC on 8 November 2006. Arrows indicate NOGAPS model winds. (Provided courtesy of JHUAPL) At right is the closest corresponding MODIS image, a Terra satellite image of the region at 1955 UTC on 7 November 2006. The 250 m pixel image is 900 pixels by 900 pixels. It shows open-cell mesoscale cellular convection with a scale similar to the SDWS signatures. (Provided courtesy of NASA)

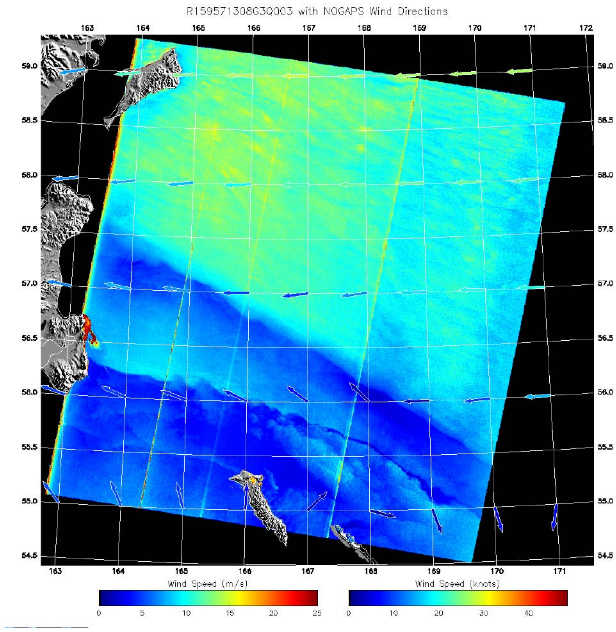

Figure 5. Radarsat-1 SDWS image depicting the near-zero-order discontinuity signatures of two synoptic-scale atmospheric fronts, both with baroclinically-driven waves. The 600 m pixel image is 1200 pixels by 1200 pixels. The image was acquired over the North Pacific at 1910 UTC on 3 April 2007. Arrows indicate NOGAPS model winds. The near-surface wind speeds increase approximately 5 m/s across each front. (Provided courtesy of JHUAPL)

were presented within *Young et al*. [2007]. A second manuscript, recently submitted to *Journal of Applied Meteorology and Climatology*, has been returned for minor revisions. A third manuscript is being prepared. Task 4, the development of a SDWS-based system for automated verification of, and error-warning system for, mesoscale near-surface wind field forecasts produced by NWP models was also completed this year. Preliminary results were presented at the 1*7th Conference on Satellite Meteorology and Oceanography* and a journal manuscript is being prepared. Task 5, the publishing of results, is ongoing via a separate expansion grant (N00014-10-1-0569). The approach taken to Tasks 3 and 4 is described in the remainder of this section with the results presented in the Results section below.

Task 3: Work continued on extending Caren Fisher's M.S. thesis research at Penn State on convectively-driven squall / lull couplets observed within SDWS imagery [*Young et al.*, 2007; *Sikora et al.*, 2009]. In that context, we developed an eight-year (1999-2006) climatology of the frequency of open cell convection over the Northeast Pacific Ocean and the thermodynamic and kinematic environment associated with its development. The climatology is based on SDWS images and global reanalysis data.

Task 4: The SDWS image filtering results from Task 2 suggested a new approach to transforming SDWS images to the same resolution as NWP model output. This approach addresses two issues with NWP model output: errors on the resolved scale and failure to resolve all mesoscale features due to limited model resolution. Both aspects of the filtering algorithm were tested this fiscal year. To assess NWP model errors on the resolved scale, a low-pass filtered SDWS image is compared with the

corresponding NWP model near-surface wind speed data. The latter are interpolated to the SDWS grid for this comparison. The product is a map of NWP model near-surface wind speed minus SDWS. Differences are due to either NWP model near-surface wind speed errors, or NWP model near-surface wind direction errors causing SDWS errors. In either case, the product highlights shortcomings in the NWP model near-surface wind field. Aspects of the SDWS that are too small to be resolved by the NWP model are quantified by high-pass filtering the SDWS image so as to eliminate the NWP model-resolved scales. Statistical metrics of both aspects of NWP model near-surface wind field error were computed as were error metrics for gale warnings derived from the NWP model results.

WORK COMPLETED

Task 1: Completed in a previous year.

Task 2: Completed in a previous year.

Task 3: Detailed observational study focused on determining the forcing, structure, and required conditions for convectively-driven open ocean squall / lull couplets frequently visible within SDWS images has been completed.

Task 4: SDWS image filtering advances from Task 2 were incorporated into the software for low-pass filtering SWDS images to NWP model resolution for detection of NWP model near-surface wind field errors. SDWS features too small to be resolved by the NWP model were mapped using the high-pass complement of this filter.

Task 5: See publication list below and the N00014-10-1-0569 annual report file.

RESULTS

Task 1: Covered in a previous report.

Task 2: Covered in a previous report.

Task 3: The climatology shows that open cell convection was a cold season phenomenon, having occurred in environments in which the difference in temperature between the near-surface air and the sea surface is negative and in environments with positive surface sensible and latent heat fluxes. Within the region between the surface and 500 hPa, the 700 hPa to 850 hPa layer median static stability was near moist adiabatic while that for the remainder was conditionally unstable. The median magnitude of vertical wind shear was largest in the 925 hPa to near surface and 500 hPa to 700 hPa layers while that at mid-levels was relatively weak. We noted similarities between the organization of open cell convection over the Northeast Pacific Ocean and tropical deep moist maritime convection in terms of cold-pool dynamics.

Task 4: Low-pass filtering was used to transform SDWS images to the resolution of operational mesoscale NWP models. A sample result is shown in Figure 6. Although the NOGAPS model captured, undiminished, the synoptic scale pre-frontal jet and frontal wind speed gradient, its low resolution eliminated the turbulence signatures and the mesoscale signatures of the individual island wakes (Figure 6A). Instead, only a widespread slowing in the immediate lee of the Aleutian chain is seen in the model analysis. Applying the high-pass complement of the filter to the SDWS image found

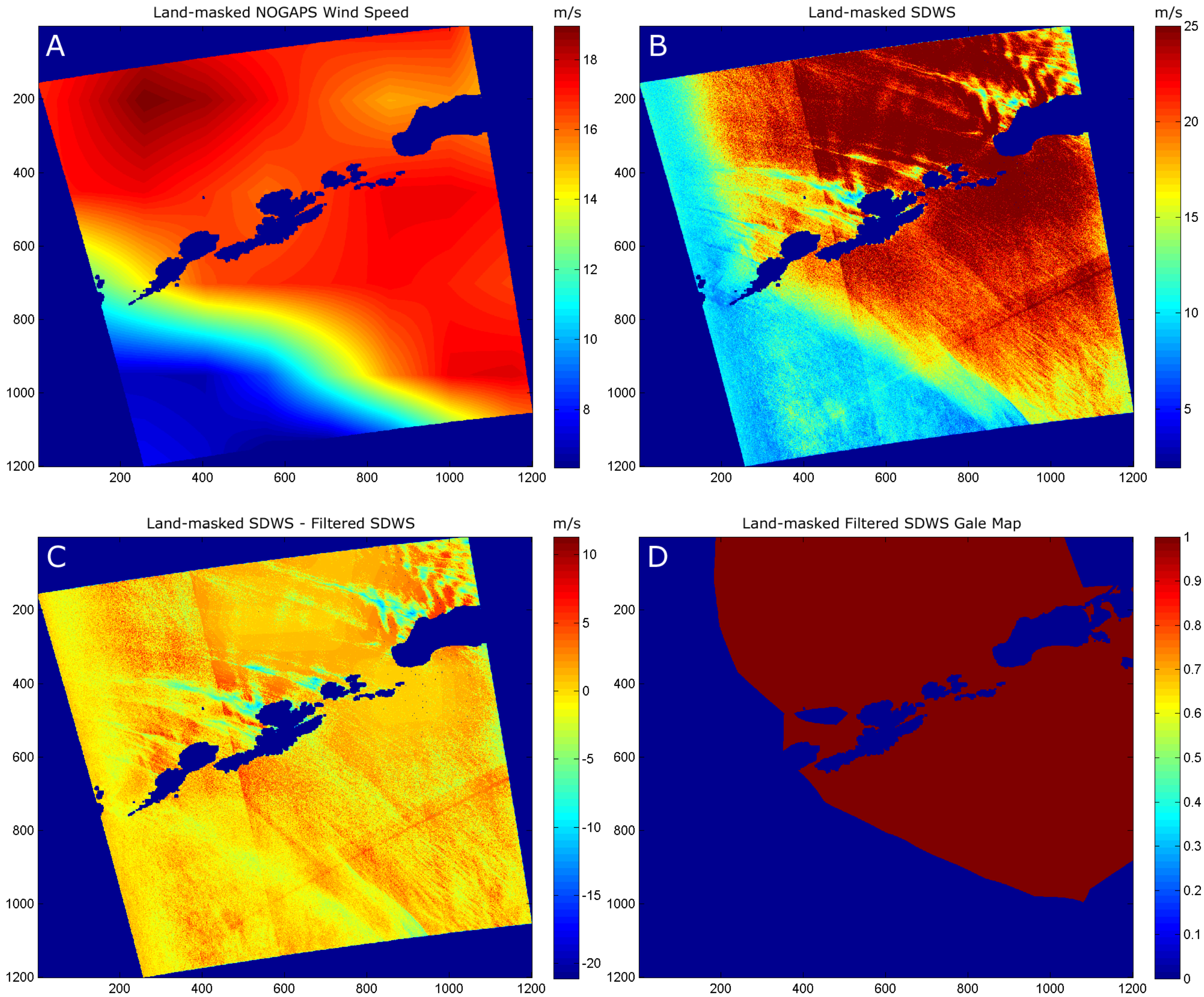

Figure 6. NOGAPS near-surface wind speed field (A), the corresponding SDWS field (B), the SDWS field filtered to show only those scales that are unresolved by NOGAPS (C), and the SDWS-based gale map filtered to include only those scales resolved by NOGAPS (D). The area contaminated by land has been masked out in blue on all four panels. These images are for the case of a strong pre-frontal jet passing over the Aleutian Islands to create intense orographic gravity waves overlaid on island wakes north of the Aleutian Islands. (Radarsat-1 SDWS image provided courtesy of JHUAPL)

in Figure 6B reveals, in Figure 6C, the full extent of the phenomena that are unresolved by NOGAPS: individual island wakes and mountain-generated gravity waves. These are the features that an operational mesoscale NWP model should be able to resolve and correctly forecast given accurate initial conditions. Figure 6D shows the SDWS gale map used to verify the NOGAPS gale warning area. The SDWS image used to derive this gale map was low-pass filtered to the NOGAPS resolution so as to depict only those features which NOGAPS should be expected to capture (i.e., the prefrontal jet). Task 5: See publication list below and the N00014-10-1-0569 annual report file.

IMPACT/APPLICATIONS

Research completed in Tasks 1 through 4 fulfills ONR objectives by making progress towards the automated integration of standard meteorological NWP model output and SAR data. Task 2 provides high-resolution analyses of near-surface wind speed, direction, and gust intensity in *in situ* data-sparse regions over the ocean, including the littoral zone. Task 4 leverages that information to use SDWS to assess the location, scale, and magnitude of near-surface wind field errors in NWP models. The observational results associated with Task 3 will lead to improved forecasts of both near-surface wind and other meteorological and oceanographic variables which can be deduced from the spatial pattern of mesoscale wind speed variability.

TRANSITIONS

The spatial filtering methods developed for Tasks 2 and 4 have been adapted for Lockheed-funded work on the detection of specific weather phenomenon using multi-spectral GOES imagery.

RELATED PROJECTS

Dr. Sikora is involved with the development of Defence Canada's Spaceborne Ocean Intelligence Network (SOIN). Defense Canada is expanding its operations to accommodate the emerging fields of ocean weather forecasting and ocean intelligence. In this regard, Defense Canada has been carrying out research into marine products that are based on remotely-sensed data from space, particularly with respect to thermal fronts, eddies, and water mass boundaries. Civilian maritime security-related operations also have critical requirements for this information. SOIN aims to synthesize those products and to addresses identified barriers to their operational use through integration with existing and planned defense and civilian security environmental operations.

Dr. Winstead is involved in an effort to make substantial improvements to the ANSWRS software package. NOAA and JHUAPL recently finalized and executed a contract agreement to re-write the ANSWRS software and SAR wind product output to meet NOAA standards for operations. Upon completion, the ANSWRS software processing stream will be declared "operational" and will be part of the NOAA data stream. A beta version of this software has been completed and is currently being tested at JHUAPL and at NOAA. This major software revision has led to the development of new standardized output SAR wind data products that meet well-defined data specifications. This standardized output is relevant for all aspects of our ONR research.

Dr. Young is part of a DTRA-funded Penn State and NCAR team addressing the mesoscale modeling of the mesoscale wind variability responsible for uncertainty in transport and dispersion of airborne contaminants such as those released during chemical and biological attacks. Dr. Young has focused on quantifying these uncertainties using all available data sources. He is also collaborating with energy system engineers and economists to quantify the impact of mesoscale wind variability on wind power and broken cloud cover on solar power generation and the resulting requirements for stabilization of the power grid.

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PUBLICATIONS

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b. New:

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